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SOVIET TECHNOLOGY ON THERMAL-MECHANICAL TREATMENT OF METALS

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SOVIET TECHNOLOGY ON THERMAL-MECHANICAL TREATMENT OF METALS

J. G. Dunleavy and J. W. Spretnak*

SUMMARY

One of the most promising methods for strengthening metallic materials that has evolved in the past 15 years is the process of thermal mechanical treatment (TMT). This process, which involves plastic deformation at elevated temperatures and retention of the "worked" structured at ambient temperature is unique--increases in strength may be attained with a gain or little loss in ductility. There are, of course, definite problems associated with the process such as the degree of temperature control required in plant operations and the negation of the TMT effect in welding processes. The exploration of TMT in the Soviet Union has followed a path somewhat different from the one that emerged in the U. S. An analysis of the Soviet effort shows the following trends:

1. The Soviet program is broad in scope covering the TMT of steels (plain carbon, low-alloy, stainless, high alloy, and tool steels), titanium, nickel, aluminum, copper and their alloys. U. S. investigators have concentrated their efforts primarily on steels (plain carbon, low-alloy, and tool steels).

2. The Soviets have explored the beneficial effects of TMT on elevated temperature properties such as creep and rupture strength of stainless and high-alloy steels and nickel and nickel-base alloys.

3. The Soviets are rapidly introducing TMT into industrial production. Several commercial rolling mills have been modified for the TMT processed rod, bar, and sheet. The TMT of tool steels for improved cutting life is apparently in the semi-production stage. Automated lines for the production of TMT treated pistons are in operation. It is anticipated that translation of their research and development programs into commercial processes will be accelerated.

INTRODUCTION

The thermal-mechanical treatment (TMT, or the Soviet equivalent, TMO) of metals and alloys is defined as the combination of a thermal treatment and mechanical deformation to produce synergistic effects, the most important of which is improvement in strength without loss of toughness. The TMT treatment can be generally classified into two categories:

(1) Deformation above the recrystallization temperature (high-temperature thermal-mechanical treatment - HTTMT - Soviet VTTMO) with a rate of cooling fast enough to preserve the deformed structure

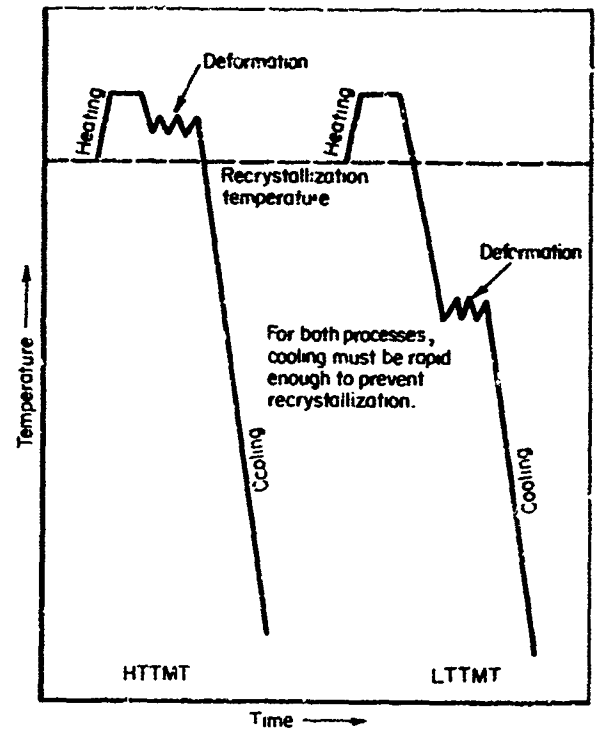

FIGURE 1. SCHEMATIC DRAWING OF HTTMT AND LTTMT PROCESSES

(2) Deformation below the recrystallization temperature (low-temperature thermal-mechanical treatment - LTTMT - Soviet NTTMO).

These processes are shown schematically in Figure 1.

The benefits to be realized by the TMT treatment have been well stated by the Soviet investigator, A. I. Khorev, who noted that "TMT is one of the most promising methods of strengthening structural metallic materials. TMT increases the strength of alloys while retaining satisfactory plasticity or increases their plasticity while maintaining the same strength level".(1)

Historically, the interest in the possible application of TMT was stimulated in 1954 by the Dutch investigators, Lips and Van Zuilen(2), who, with the aid of LTTMT, produced steel wire with an ultimate tensile strength over 400,000 psi. This classic work sparked a host of U. S. investigations which established this procedure as a new method of strengthening. Considerable effort has been directed to the understanding of the operative mechanisms in the process.(3-12) The LTTMT process designated as "Ausforming" (a copyrighted term) was patented by Schmatz, Shyne, and Zackay of the Ford Motor Company in 1960.(13)

Although the early U. S. effort in TMT represents an impressive amount of work, it was narrow in scope. All of these investigators, with the exception of Grange and Mitchell(7), were concerned with the application of LTTMT in the achieve-

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ment of high strength levels in heat-treatable alloy steels. Grarge and Mitchell, on the other hand, studied the HTTMT of steel and the gains attainable on subsequent transformation and tempering. This pattern of effort on LTTMT established in the United States during the middle 1950's continued unchanged until well into the middle 1960's. Eventually, the realization came that the TMT process is not limited to steels and the attainment of high strength, but encompasses many metal systems and yields interesting combinations of properties. The broadening of the concept of TMT in the United States can be attributed, in part, to the availability of translated Soviet publications in this field. Unfortunately, much of the present U. S. work in HTTMT is of a proprietary nature, and consequently, has not appeared in open publications.

These preliminary remarks on the U. S. effort in the field of TMT are not to be construed as derogatory in nature, but are presented as an example of what can occur when the investigation of a new phenomenon is narrow in scope. The U. S. work on LTTMT has been excellent and quite comprehensive. Remarkable gains in strength and toughness have been achieved in a number of steels by employment of a variety of deformation processes (rolling, forging, drawing, and spinning).[11] In fact, the potential gains in strength through application of LTTMT are appreciably higher than can be realized in HTTMT. However, the very nature of LTTMT imposes severe restrictions on its commercial application to steels. The deformation temperatures are low, 700 to 1100 F, and deformation pressures consequently are high. Temperature control also becomes critical and the permissible temperature range often is not compatible with good production-control standards. In addition to these limitations, a concentration of effort on LTTMT would not open up the broader aspects of TMT, namely, its application to metallic alloys other than steels.

The Soviet entry into the field of TMT was not prompted by a desire to produce higher strength metallic materials but was an unexpected spin-off from a long-range study on the temper brittleness of steels. During this program, the Soviets found that an HTTMT treatment alleviated temper brittleness Further study showed that HTTMT significantly raised the toughness level. At this point, the Soviets initiated a program devoted to the effects of TMT in various metallic systems and to gaining an understanding of its mechanism.[14-19] As the program progressed, the Soviets studied the theoretical aspects of both LTTMT and HTTMT.

The U. S. interest in TMT has quickened in the past few years largely as a result of the development and production of dual-purpose, lightweight steel armor utilizing LTTMT and the desire to increase the reliability (toughness) of high-strength aerospace components utilizing HTTMT.[20]

BASIC MECHANISMS UNDERLYING THE PHENOMENON OF THERMAL-MECHANICAL TREATMENT

A mechanism that rigorously explains the relationship between the reactions that are operative in TMT and the resulting changes in mechanical properties has not been formulated to date. However, on the basis of the research efforts in the U.S.S.R. and the United States in this area, the mechanism can be explained in qualitative terms.

Subjecting a metal such as a steel to TMT produces a "worked structure" that is retained to some extent at room temperature. The presence of this "worked structure" is responsible for the increase in mechanical properties (strength and/or ductility) over those attained through a normal quenching and tempering treatment or through a combination of cold work and subsequent heat treatment. In addition, TMT usually increases the resistance of the steel to fracture and, in some instances, its resistance to corrosive environment. These statements apply to both HTTMT and LTTMT.

At the present time, it is known that the production of a "worked structure" by the TMT process results in an elongation of the grains of the high-temperature structure (austenite in steels), generation of a stable substructure, serration of the grain boundaries of the substructure, and an increase in dislocation density of the substructure. This stable substructure that was formed by deformation, relaxation, polygonization, and diffusion is transferred to the lower temperature phase (martensite in steels). As a consequence, shape, spacing, and carbon content of martensite platelets, for example, are altered. These alterations in turn are reflected in the tempered martensitic structure. In nonmartensitic alloys, for example, precipitation-hardenable alloys, the shape and size (morphology) and distribution of the precipitates are altered. The result of these structural alterations is usually an increase in strength and/or ductility and resistance to fracture

SOVIET BASIC RESEARCH ON THERMAL-MECHANICAL TREATMENT

The Soviet efforts at understanding the phenomenon of TMT began with the V. D. Sadovskiy school in 1955.[14] Their contributions were significant because they eliminated many of the initially incorrect assumptions and established a firm foundation for the subsequent work in the field.[14-19]

Following the initial efforts of the Sadovskiy group, basic research on thermal-mechanical treatment of metals and alloys proceeded on a broad front. The effort can be categorized into the following subject areas: (1) theories of strengthening, (2) characteristics of deformed austenite, (3) heredity effects in TMT, (4) improvement of elevated-temperature strength, (5) TMT for titanium alloys, (6) effect of TMT on corrosion resistance, and (7) combined thermal mechanical and magnetic treatment.

Theories of Strengthening

One of the earliest suggestions for the strengthening effect of TMT was the strengthening of the austenite grain boundaries by serration.[21,22] Serration of the boundaries reportedly changes the fracture mode from intergranular to intragranular. Slip traces are eliminated during deformation of the stable austenite ("healing"). The serrations are formed during slip by diffusional shift of some sections of the boundary. As the deformation temperature is increased, the period and amplitude of serrations is also increased. The observed preferential formation of substructure along grain boundaries indicates that deformation is localized (more intense) at the boundaries than in the body of the grains.

Following this initial Soviet attempt at the statement of a reasonable mechanism, at least six other hypotheses were proposed to explain the strengthening effect:

(1) A decrease in the austenitic grain size and a corresponding refinement of the martensite plates.

(2) A decrease in cell size (size of coherent scattering areas)

(3) Precipitation of carbides during deformation of austenite.

(4) The generation of microstresses

(5) Increased dislocation density

(6) An advantageous orientation of the martensite plates.

As might be expected, considerable disagreement has been associated with these hypotheses in the U.S.S.R. However, as shown below, general agreement has been reached in most of the disputed areas in recent years.[23,24]

The Soviets now believe that microstresses do not play an important role in strengthening. Deformation creates substructures and breaks up the grains; this process is enhanced by the quenching. The martensite formed after TMT is very fine, the dislocation density is high, and the cell size is very small. Lattice transformation occurs by the action of partial dislocations.[25] The dislocation density in martensite depends on the corresponding density in austenite; there is dislocation multiplication during the transformation. The dislocation structure in austenite is inherited by the martensite.[26] The dislocation density increases with an increasing number of steps or passes for a given degree of total deformation. Strengthening from TMT is directly related to a considerable reduction in cell size and martensite grain size and increased dislocation density, particularly in the form of dislocation arrays.[27] No further increase in strength occurs during tempering of martensite.[28]

Investigations of LTTMT by Ya. M. Potak showed that the size of martensite plates is reduced by a factor of 2-3 and the cell size by a factor of 2-4.[29] He put forward an equation for the strengthening effect in terms of the dimensions of the martensitic plates; in this case, the strength varied as the reciprocal of the square root of the plate length. Later investigations showed that the refinement of martensite is not the chief reason for strengthening but a secondary effect. Strengthening occurs during the deformation of austenite; the degree of hardening depends on the temperature of deformation and the carbon content of the steel. The structure of the austenite is inherited by the martensite.[30,31]

With deformation of austenite up to 25 to 30 percent, carbide precipitation is not extensive and the amount of residual austenite increases. With larger amounts of deformation, precipitation of carbides predominates, the Ms* is increased, and the amount of residual austenite is decreased.

*Ms - the temperature at which the martensite reaction begins.

Particular emphasis has been given to increasing the ductility of superstrength steels by polygonization annealing after LTTMT treatment. In this treatment, the steels are austenitized, cooled quickly to 550 C, deformed 30 to 37 percent, and reheated immediately to 550 to 700 C for times ranging from 0 to 5,000 seconds (the polygonization anneal). The strength is only slightly increased, but the ductility is increased significantly.[32]

Characteristics of Deformed Austenite

The Soviets have expended considerable effort on the investigation of the austenite deformed during TMT in the hope of improving the process. To date, they have found that, in LTTMT (metastable austenite temperature range), elastic strains only tend to accelerate the transformation while plastic strains rapidly accelerate transformation; the rate of acceleration increases with increasing strain rate.[29,33]

On the basis of the observations of several Soviet investigators, it now is known that HTTMT produces the following changes: (1) there is a more complete solution of excess phases during solution treatment, (2) there is a more complete precipitation during aging, (3) the cell size is refined, (4) a considerable microdeformation is created, and (5) more axial texture is found (i.e., the preferred direction of (111) planes is in the axial direction). Sokolkov, et al., found that the austenite grains are "pancake shaped".[34-36] Additional investigations on the nature of austenite subjected to TMT showed that strength increased as the temperature of deformation decreased. The increase in the strength of the steel after quenching is one-half of the increase in the strength of austenite, and the yield strength of deformed austenite starts to decrease at about 150 degrees above the deformation temperature for holding times of 30 minutes.[37]

Recrystallization of the deformed austenite essentially nullifies the strengthening effect of TMT. However, manganese and nickel decrease the recrystallization rate, particularly at low carbon levels. Increasing the carbon content reduces the beneficial effect of the manganese and nickel.[38] As might be expected, the self-diffusion rate in the austenitic range is increased by a factor of 2.0 for bulk and 3.0 for grain-boundary diffusion.[39] In plain carbon steels, the problem of realizing maximum strengthening from TMT (only HTTMT is practical in this instance) is difficult because of the rapid onset of recrystallization (there is high mobility of dislocations). However, it was found that an AISI 1020-type steel simultaneously impact deformed and quenched could be strengthened appreciably. Examination of the substructure showed that a multiplication of dislocations had occurred during the transformation.[40]

The amount of internal energy stored in TMT was compared with that stored by conventional cold work.[41] The amount of energy stored in Armco iron during HTTMT was about 1.5-2.0 times higher than the levels reached during cold working.

Hereditary Effects in Thermal-Mechanical Treatment

The reported hereditary effects of TMT have been the subject of disagreement among Soviet investigators. M. L. Bernshteyn claims that the steel processed by TMT can be softened by a high-

temperature tempering treatment to facilitate machining and forming and then rehardened without serious loss of the TMT strengthening effect.(41,42) The factors involved in the preservation of the "worked structure" are (1) refinement of grains, (2) crystallographic texture, (3) dislocation texture, and (4) precipitation texture. V. Ya. Zubov and his colleagues stated in an article on problems associated with "heredity" they had found that spring steel did not exhibit the "heredity effect". Additional tempering and annealing of TMT-treated springs eliminated the beneficial effects of TMT. In fact, an increase in brittleness was encountered.(43) This controversy is an illustration of the knowledge gaps that exist relative to TMT. U.S. publications on this aspect of TMT have not appeared to date.

Improvement of Elevated-Temperature Strength

One of the problems of continued interest to the Soviets is the improvement of the elevated-temperature strength of metals and alloys. The possible application of TMT to this problem was studied by the Soviets, and beneficial effects were found. Up to the present, if the TMT-treated material is utilized above the recrystallization temperature, the beneficial effects, such as longer stress-rupture life at higher stress levels, tend to fade away. However, interesting improvements have been realized and utilized by Soviets within these limitations.

Improvement of elevated-temperature properties is the result of fragmentation of particles of the strengthening phase, a more complete decomposition of the solid solution, and changes in the structure of the alloy.(30). It is claimed to be beneficial for blading material operating at modest temperatures. The following treatment is recommended for a 12Cr-2Ni-1W-0.5Mo-0.3V steel: 60 percent deformation by stamping at 1010C, quench, swage an additional 5-10 percent and temper at 600 C. Other pertinent investigations include a treatment for heat-resistant alloys 77Ni-1Cr-1Al-0.5Ti and 70Ni-1Cr-1W-1Al-1Mo-0.5Ti.(44) These alloys are deformed 0.15 to 5.0 percent at 600 C (1110 F) and annealed at 600 C for 100 hours. After this treatment they were deformed a very small amount at a relatively low temperature

The optimum substructure was found by means of internal friction measurements. The most stable polygonal structure, which corresponds to maximum elevated temperature properties, occurs at the minimum value of internal friction.

Thermal-Mechanical Treatment for Titanium Alloys

The application of TMT to titanium alloys was a natural step for the Soviets from their initial work on steels, as the titanium systems encompass aging reactions and a martensitic transformation. In addition, titanium alloys represent an important group of structural materials for defense and civilian applications. Accordingly, a considerable amount of research-and-development effort has been expended on these materials. However, the investigations were for the most part of a developmental nature and directly connected with defense applications, as discussed in the Development and Applications section of this memorandum.

Soviet attempts to understand the strengthening of titanium alloys by TMT have been limited, but the results have been revealing. In alpha + beta alloys, HTTMT usually produces an increase in strength and ductility or increase in ductility at approximately the same strength level. For example, in Ti-4Al-2Cr-2Mo, the strength and ductility are increased, but, in a Ti-1.5Al-1.5Mn alloy, relative elongation and reduction of area increase with a slight drop in strength. Apparently, HTTMT increases the amount of the beta phase and the amount of distortion in the alpha-prime phase.(45) Alloys of the Ti-6Al-3Mo and Ti-4Al-3Mo type, processed by HTTMT (specifically, hot pressing at high temperatures) in the alpha + beta region and quenched prior to solution treatment and aging, have improved strength and ductility. HTTMT in the beta field for these alloys raises the ductility with little change in strength.

The changes in the structure of the alloys subjected to HTTMT prior to solution treatment and aging are significant. The amount of alpha-prime phase is increased, the defect structure is considerably denser, and the defect structure of the alpha-prime phase formed from the beta phase is stable. Apparently, this stability results from annihilation of dislocations during lattice transformations.(25)

In alloys with an all-beta structure, such as Ti-3Al-6.5Mo-11Cr, LTTMT after solution treatment and prior to aging appears to affect the aging reaction. The aging process is accelerated (the decomposition of beta to alpha is more intense at any given aging time and temperature).(46) In addition, the microstructure is affected by the degree of deformation. At the reduction of 20 percent, grain boundaries are still intact, but, at 40 percent reduction, grain boundaries become indistinguishable metallographically.

The most beneficial effects gained from the application of LTTMT to the beta titanium, other than an increase in strength, are the shortening of the aging process and the decrease in sensitivity to variations in time and temperature for solution treatment and aging. As a consequence, the mechanical properties of the heat-treated alloys are more uniform, industrial heat-treatment schedules are easier to maintain, and the response of the alloys to applied loads is more predictable; also, the resistance to corrosive attack is increased.

The Effect of Thermal-Mechanical Treatment on Corrosion Resistance and Hydrogen Embrittlement in Steels

Only a few investigations have been reported in this area, so precise evaluation cannot be made yet. However, one Soviet publication has reported a small increase in the corrosion resistance of AISI 1045 and 0.6C-2Si steels in an aqueous solution of sulfuric acid.(47) Improved corrosion-fatigue resistance in various steels also was reported.(48) Generally, lower corrosion resistance would be expected from TMT as compared with cold working, in view of reports of more internal energy storage by TMT.(41) The susceptibility of structural steels to hydrogen embrittlement was not affected by TMT.(49)

Combined Thermal-Mechanical and Magnetic Treatment of Metals and Alloys

A limited amount of Soviet work has been reported on the combined effect of TMT and magnetostrictive forces. Although this combined treatment does not yield spectacular increases in properties over TMT, it does intensify the action of TMT on metallic structures. The presence of a magnetic field during TMT increases fragmentation of the grains and further refines the structure.[50] With combined treatment on steels, ductility and true fracture strength are increased and the tendency to temper brittleness is decreased. The practical application of the combined treatment falls into a marginal area where the benefits gained would have to be carefully considered relative to the economics in each potential application.

SOVIET WORK ON DEVELOPMENT AND APPLICATIONS OF THERMAL-MECHANICAL TREATMENT

In the final analysis, the value of any process is judged on the ease with which it can be incorporated into commercial production. Consequently, the present and future status of TMT in this area will determine its importance in the economy of the U.S.S.R. and, more specifically, in the fabrication and production of air weapons and defense weapon systems. At the present time, evidence of production application of TMT in the U.S.S.R. has been sparse. TMT with a few notable exceptions, appears to fall largely in the development or pilot-plant stage.

Steels

Steels constitute the major metallic material of construction in any economy and, consequently, receive the greatest amount of development and application effort. TMT in the U.S.S.R. follows this normal pattern of activity. For purposes of this discussion, steels are classified into the following groups: carbon steels, low-alloy steels, stainless steels, tool steels, and specialty steels.

Carbon Steels

Soviet work on TMT of this class of steels has been almost entirely limited to pilot-plant or semiproduction types of investigations. These investigations were conducted in steel mills on production equipment. The steels of interest were the medium- to high-carbon grades that are equivalent to such U. S. steels as AISI 1040, 1060, and 1090. The structural shapes largely have been rounds and bars from which semifinished or finished products could be fabricated. The majority of the effort has utilized HTTMT, with LTTMT being confined primarily to the production of wire.

In all instances reported, the application of TMT produced substantial increases in strength. For example, in an AISI 1060-type steel subjected to HTTMT and tempered at 200 C (390 F), the ultimate strength rose about 190 percent over that attained by normal quenching and tempering. At a tempering temperature of 400 C, the increase in strength was about 140 percent. At the higher strength levels, ductility (expressed as relative elongation) increased slightly as compared with that obtained from normal heat treatment, and at lower strength levels, the elongation often doubled. Increases in notched-bar impact strength range from 1.5 to 2 times.[51] Similar experiences were encountered with AISI-1040 and -1090 types of steel.[52-54] A production line for the processing of AISI 1040-type steel for pistons in oil well pumps is in operation at the Krasnyy Oktyabr plant.[53] In this operation, cooling stations are located directly behind the rolling mill to cool the bar stock rapidly from the rolling temperature to the temperature selected for an additional LTTMT treatment. The resultant bar stock that has been subjected to HTTMT and LTTMT showed increases in strength of about 1.5 times and slightly higher elongation and notched-bar impact strength than was obtained by conventional oil quenching and tempering.

It is apparent that the Soviets are actively attempting to incorporate TMT into the commercial production of carbon steel well-drilling products. The greatest returns will be encountered in the medium- and high-carbon grades. The application of TMT to low-carbon steels is difficult on a production basis because of the rapid onset of recrystallization and subsequent loss of the "worked-structure" produced by TMT and the strengthening effect it produces.

The Soviets apparently are well aware of these practical limitations of TMT and, consequently, have concentrated their efforts on the medium- and high-carbon grades. In addition, they have confined their initial efforts to definite end products such as the fabrication of pump pistons from TMT processed bar stock. This practical engineering approach to the exploitation of a new process enables production personnel to gain considerable knowledge in the application of TMT without excessive alteration of production equipment or scheduling.

Low-Alloy Steels

The low-alloy steel grades encompass the high- and ultrahigh-strength structural steels of particular interest in structures for aircraft, rocket casings, and ordnance. These particular steels, because they usually are incorporated into structures that operate in an environment of complex dynamic loadings, are often highly susceptible to premature failure (failure at loads below the design level). In many instances, these failures are of a catastrophic nature. The advent of TMT offered a partial solution to this general problem area, as it was a process that could raise the strength and ductility level, raise the strength level with only minor losses in ductility, or raise the ductility at the same strength level.

In the U. S., research-and-development effort was concentrated on LTTMT, the process that yields the highest gains in strength. Unfortunately, LTTMT is more difficult to incorporate into a production fabrication process than is HTTMT. If the temperature of deformation is too high, the advantage of LTTMT is lost; on the other hand, if the temperature is too low, there is a good possibility that either the deformation equipment (for example, rolls) or the metal will fracture. The acceptable temperature range is quite narrow. In addition to these problems inherent in the application of LTTMT to low-alloy, high-strength steels, a suitable method of joining thermal-mechanically treated components for fabrication and assembly into a structure has not been developed. To date, only mechanical fastening

and adhesives are available for the joining of TMT components. Joining by welding obliterates the strengthening effect of TMT. In recent years, considerable work has been done in the United States on the use of electron-beam welding as a means of decreasing the weakened zone of the weld; however, the weakened zone cannot be eliminated by this process.[55] In addition, the electron-beam welding process has severe physical limitations. Nevertheless, electron-beam welding offers a solution for the problems involved in the joining of TMT-processed components in specific instances.

A sharp line of demarcation exists between the Soviet work on carbon steels and low-alloy steels. Activity on carbon steels was directly involved with production facilities and production personnel, while the activity on low-alloy steels was confined primarily to research institutes and research investigators. This difference in approach is the reflection of two conditions: (1) the initial work on TMT was done on low-alloy steels by researchers and (2) the production exploitation of TMT for this class of steels is more difficult than it is for carbon steels. Consequently, if the high increases in strength possible with TMT are the primary objective, then the rapid exploitation of TMT in the area of low-alloy, high-strength steel components and structures does not appear likely in the near future except for very specialized applications. However, if the primary objective is an increase in reliability under dynamic load (as expressed by fracture toughness) with modest increases in strength, then production exploitation of HTTMT could be quite readily realized. In addition increases in the abrasive wear resistance of structural steel after HTTMT have been reported.[56]

Soviet work on the TMT of low-alloy steels can be classified conveniently into HTTMT and LTTMT. The following discussion will be so presented and will allow a comparison of the changes in mechanical properties obtained by the two variations of the same general process.

High-Temperature Thermal-Mechanical Treatment (HTTMT). The process designated as HTTMT consists of plastic deformation of the steel above the recrystallization temperature (in the austenite field) followed by rapid enough cooling to maintain the "worked-structure" at room temperature. Initially, Soviet investigators on HTTMT were associated with a long-range program on the irreversible temper brittleness of steels (temper brittleness encountered in the temperature range of 450-600 C). HTTMT was successful in alleviating the harmful effects of temper brittleness, and it is used in the U.S.S.R. at the present time to augment the beneficial effects of molybdenum and tungsten additions.[14-19] During the course of this work, it was noted that interesting increases in strength and toughness also were gained by HTTMT. Consequently, several groups of Soviet investigators began studying this phase of the phenomenon about 1958. A schematic diagram of the HTTMT process is shown in Figure 1.

Typical examples of the data generated on the tensile properties and toughness of low-alloy, high-strength steels are given in Table 1.[37,38,42,45,57,58] Significant increases in tensile and yield strength, as well as relative elongation, reduction of area, and impact strength, are obtainable. The data presented in Items 4 and 5 of Table 1 are representative of Soviet investigations directed toward improvement of toughness as rated by the notch-bar impact tests. A doubling of the impact strength by HTTMT and a lowering of the ductile-brittle transition temperature are normally expected. These increases in impact strength usually are maintained over a range of testing temperatures as shown in Figure 2. The beneficial

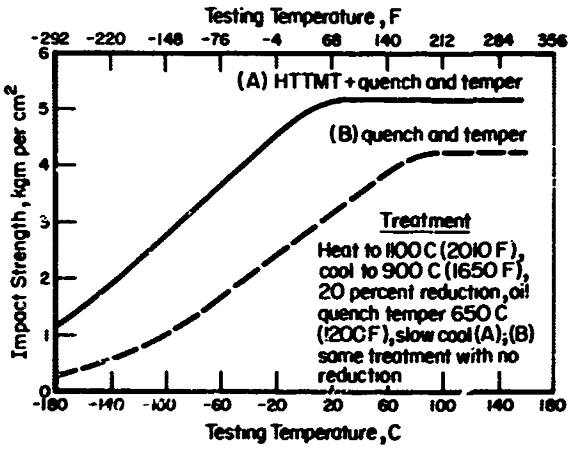

FIGURE 2. THE EFFECT OF HTTMT ON IMPACT STRENGTH OF AN AISI4340-TYPE SOVIET STEEL

effect of HTTMT on impact strength is maintained over a range of strength levels. Inspection of Figure 3 shows that as impact strength is increased by TMT the irregularities in impact strength resulting from irreversible (500-600 F embrittlement) and reversible (800-1000 F embrittlement) temper brittleness either are eliminated or alleviated. The effect in a specific instance is related to the type of steel. For example, Figure 3 shows that the effect of the temper-embrittlement regions is eliminated in the 0.4C-4Ni and greatly reduced in the 0.35C-1Cr-1Mn-1Si steel.

A completely satisfactory explanation for the increases in toughness produced by TMT has not been presented to date. However, important factors involved in this increase include the serration of substructure grain boundaries and the high density of unpinned dislocations.[59] The former should increase resistance to crack propagation and the latter should increase resistance to crack initiation through the inhibition of mechanical twinning, and resistance to slip and crack propagation should be increased by promoting local plastic relaxation at the crack tip.

The increase in strength level attainable by TMT over that realized by a normal quench-and-temper treatment is controlled by the degree of deformation. The actual levels of strength obtained and the rate of strengthening are related to the specific steel in question. Typical examples of the relationship between the degree of deformation and tensile properties are given in Table 2. The relative effects of HTTMT, LTTMT, and a normal quench-and-temper treatment are readily seen in these data. For example, the strength and ductility of the Soviet steel 0.37C-1.3Cr-4Ni are increased for both HTTMT and LTTMT over

TABLE 1. TYPICAL RESULTS OBTAINED ON SOVIET LOW-ALLOY, HIGH-STRENGTH STEELS SUBJECTED TO HTTMT[37,38,42,45,57,58]

Item No.	Type of Steel	Treatment	Strength, ksi Ultimate	Strength, ksi Yield	Elongation, percent	Reduction in Area, percent	Notched-Bar Impact[(a)] Strength, kgm/cm²
1	0.5C-1Cr-1Mn-0.05Ti	Oil quenched, tempered 300 C (570 F)	243	216	0	0	- -
		25% reduction by hot rolling at 890 C (1635 F), oil quenched, tempered 300 C (570 F)	280	250	4.7	26	- -
2	0.55C-1Cr-1Ni-1Mn-0.05Ti	Oil quenched, tempered 250 C (480 F)	258	230	0.7	8	- -
		25% reduction by hot rolling at 890 C (1635 F), oil quenched, tempered 250 C (480 F)	295	250	4.5	20.3	- -
3	0.5C-1.6Cr-4Ni-0.3Mo	Oil quenched, tempered 100 C (212 F)	254	222	16	10	2.5-12.5
		90% reduction by forging at 900 C (1650 F) oil quenched, tempered 100 C (212 F)	400	270	24	22	4-20
4	0.3C-1Cr-1Mn-1Si	Oil quenched, tempered 400 C (750 F)	- -	- -	- -	- -	7-35
		Heat to 1150 C (2100 F), cool to 900 C (1650 F) 20% reduction by rolling, oil quenched, tempered 400 C (750 F)					
5	0.37C-1Cr-3Ni	Oil quenched, tempered 400 C (750 F)	- -	- -	- -	- -	2.5-12.5
		Heat to 1150 C, cool to 900 C (1650 F) 20% reduction by rolling oil quenched, tempered 400 C (750 F)	- -	- -	- -	- -	5-25

(a) An approximate conversion for these steels is 1 kgm/cm² = 3 foot-pounds V-notch Charpy impact.

those obtained by a normal quench-and-temper treatment. However, Soviet steel 0.4C-1.4Cr-1.6Ni-0.8W was not appreciably strengthened by HTTMT but the ductility increased. LTTMT raised the strength level of this steel while maintaining about the same level of ductility. Toughness as expressed by the notched-bar impact test would be increased for both TMT methods over those obtained by a normal quench-and-temper treatment.

The gains in strength with HTTMT are not as spectacular as those achieved with LTTMT; however, losses in ductility and toughness are rarely encountered. Soviet investigators connected with applications requiring high strength-to-weight ratios probably devoted their initial activities to the HTTMT process because it yields the greater gains in strength. The most recent Soviet work on the TMT of low-alloy, high-strength steels has been directed toward a combined HTTMT and LTTMT treatment. This does not imply, however, that the Soviets have stopped investigations on the HTTMT of these low alloy, high-strength steels. For example, the results of a comprehensive investigation on the relationship of the metallurgical structure produced by HTTMT in a 0.47C-1.5Cr-0.9Mn-1.8Si-0.1Mo steel was published in 1967.[60] The investigators found that the amount of the retained austenite in the quenched-and-tempered HTTMT steel was higher than in steel quenched and tempered without HTTMT. An additional quench and temper, however, lowered the amount of residual austenite below that of steel not subjected to HTTMT. This is important, as it points out the possiblity of using multiple heat treatment to realize even higher gains in strength and toughness from HTTMT

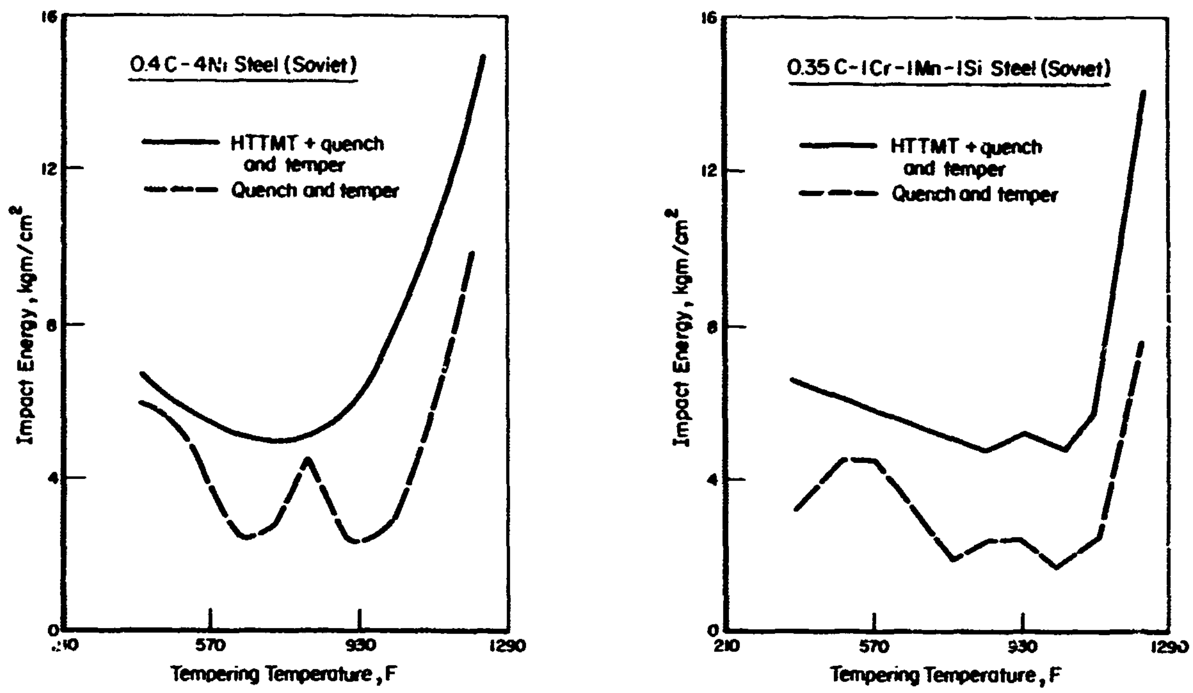

FIGURE 3. THE EFFECT OF HTTMT ON IMPACT STRENGTH[58]

TABLE 2. THE RELATIONSHIP BETWEEN TENSILE PROPERTIES AND DEFORMATION DURING TMT FOR TWO SOVIET STEELS[45]

(Tempered at 200 C (390 F))

Type of Steel	Deformation, percent	Tensile Strength, ksi			Reduction in Area, percent		
		NT[a]	HTTMT[b]	LTTMT[c]	NT[a]	HTTMT[b]	LTTMT[c]
0.37C-1.3Cr-4Ni	0	248			30		
	10		289	325		38	30
	30		293	342		38	29
	50		298	352		36	27
	70		303	360		33	25
	80		304			30	
0.4C-1.4Cr-1.6Ni-0.-W	0	265			32		
	10		265	280		35	30
	30		267	306		40	32
	50		268	312		45	33
	70		273			45	
	80		280			45	

(a) NT - Normal treatment (quench and temper)

(b) HTTMT - Deformed at 930 C (1705 F)

(c) LTTMT - Deformed at 550 C (1010 F)

steels. The "hereditary effect" of TMT was also noted in this investigation, as the effects of HTTMT were not eliminated despite a double quench-and-temper treatment. Prior Soviet work showed that in HTTMT (also generally applicable to LTTMT) the amount of retained austenite varies with the amount of deformation, reaching a maximum of about 20 to 25 percent.[30] Above 25 percent deformation, the ability of the austenite to form slip bands increases. Consequently, the number of nucleation sites available for carbon precipitation increases with an attendant reduction in carbon content of the austenite. Simultaneously, the M_s temperature increases and the amount of retained austenite decreases.

Low-Temperature Thermal-Mechanical Treatment (LTTMT). The process designated as LTTMT consists of heating the steel to the proper temperature for austenitizing, cooling it below the critical point, A_3, deforming the steel in this metastable region, and cooling it rapidly enough to maintain the "worked" structure produced by deformation. A schematic diagram of the LTTMT process is shown in Figure 1.

One of the basic problems inherent with steels processed by LTTMT - - low ductility- - is well illustrated in Table 3. In only one instance, with a 0.48C-0.6Cr-2.2Ni-1.2Mn-1Si-1W-0.5Mo steel, is an increase in elongation obtained, and, in all instances, the reduction in area drops after LTTMT. Although the loss in ductility values are relatively small, the ductility values of the steels processed by a normal quench-and-temper treatment are barely adequate. Consequently, when the strength levels are raised by LTTMT from 50 to 100 percent, the accompanying ductility levels are often not adequate. Only when polygonal annealing* is incorporated into the LTTMT schedule, as shown further on, is there a gain in both strength and ductility.

LTTMT was applied to steel SP-43** in a very specific manner.[64] One-tenth-inch-thick SP-43 was welded, and, as the weld zone cooled, it was plastically deformed. Optimum properties were achieved at a weld-seam temperature of about 800 C (1470 F) and a deformation of 15 percent. This treatment raised the properties of the weld seam up to those of the base metal. The authors recommend that the process receive further development to ensure its practical application.

Many of the Soviet low-alloy high-strength steels have been the subject of LTTMT investigations.[32,36,61,62-65]. Among these are:

VL1 - 0.3C-1Mn-1Si-1.7Cr-2Ni-1.2W-0.45Mo

VL1D - 0.3C-1Mn-1Si-1.4Cr-1.2Ni-0.8W-0.45Mo

TABLE 3. TYPICAL RESULTS OBTAINED ON SOVIET LOW-ALLOY HIGH-STRENGTH STEELS SUBJECTED TO LTTMT[37,57,61-66,67]

Type of Steel	t_a(a) C	t_a(a) F	t_d(b) C	t_d(b) F	ε(c), percent	t_T(d) C	t_T(d) F	Tensile Strength, ksi Ultimate	Tensile Strength, ksi Yield	Ductility, percent Elongation	Ductility, percent Reduction in Area
0.48C-0.6Cr-2.2Ni-1.2Mn-1Si-1W-	1000	1830	550	1010	90	100	212	417	293	6	- -
0.5Mo	1000	1830	- -		0	100	212	251	206	2	- -
0.42C-1.9Cr-1.4Si-4.2Ni-0.48Mo-	950	1740	525	975	75	200	390	320	286	1.5	43
0.25V	950	1740	- -		0	200	390	285	219	3	45
0.41C-1.7Cr-1.4Si-4.5Ni	850	1560	525	975	75	220	410	460	363	5	35
	850	1560	- -		0	220	410	254	181	- -	- -
0.35C-1.5Cr-3.5Ni-0.4Mo-0.25V	- -	- -	600	1110	93	200	390	376	362	11	36
	- -	- -	- -		0	200	390	250	209	10	41
0.4C-5Cr-0.5Mo-0.3V	- -	- -	600	1110	93	350	660	374	348	10	40
	- -	- -	- -		0	350	660	273	274	14	42
0.37C-1.5Cr-3.5Ni	1150	2100	550	1010	75	150	300	390	327	3.5	22
			- -		0			290	223	5	26
	1150	2100	430	895	80	100	212	341		7	25
0.4C-1.5Cr-4.3Ni-1Si-0.45Mo	1150	2100	450	840	75	150	300	375	250	5	- -
	1150	2100	- -		0	150	300	341	209	9	- -
0.3C-1.3Cr-1.5Ni-0.4Mo	1150	2100	500	- -	50	200	390	293	259	6	20
	1150	2100	- -		0	200	390	250	210	10	38
0.3C-1.2Cr-1.3Mn-1Si-1.4Ni	- -	- -	550	- -	70	275	525	352	318	8	- -
	- -	- -	0		0	275	525	293	250	11	- -

(a) t_a= Temperature of austenitizing.
(b) t_d= Temperature of deformation.
(c) ε= Degree of deformation, percent.
(d) t_T= Temperature of tempering.

* Polygonal annealing : stress relaxation without recrystallization.

** Composition given in the following paragraph.

VKS1	- 0.3C-0.8Mn-1.2Si-1.4Cr-0.7Ni-0.5Mo-0.05V
40KhGSNVF	- 0.4C-1Cr-1Mn-1Si-1Ni-1W-0.25V
40KhSNVF	- 0.4C-1Cr-1Si-1Ni-1W-0.25V
SP-28	- 0.28C-3Cr-1Si-1Ni-1W-0.4Mo-0.25V
SP-43	- 0.43C-3Cr-1Si-1Ni-1W-0.4Mo-0.25V
25Kh2GSNVM	- 0.25C-2Cr-1Mn-1Si-1Ni-1W-0.4Mo

Steels VL1, VL1D, VKS1, 40KhGSNVF, and 40KhSNVF were raised to high levels of tensile and yield, but the ductility and toughness values were marginal.(32,65) Steels SP-28 and 25Kh2GSNVM were processed by LTTMT, immediately reheated to a temperature of 550-700 C (1020-1290 F), and held at that temperature for times up to 5000 seconds. Optimum properties were achieved with this polygonal anneal at 600 C (1110 F) for 100 seconds. A comparison of normal-treatment quench and temper (NT), LTTMT, and LTTMT + polygonal anneal (PA) are given below for steel SP-28:

	Tensile Strength, ksi	Reduction of Area, percent
NT	290	17
LTTMT	316	26
LTTMT + PA	320	34

This particular investigation presented a design for continuous LTTMT + polygonal anneal on a rolling mill.

The program on the polygonization of high-strength steels subjected to LTTMT has continued up to the present.(66,68,69) In the most recent work, steels SP-28, 0.25C-2Cr-1Mn-1Si-1Ni-1W-0.4Mo, and SP-38 (a 0.38 C version of SP-28) were intensively studied for the relationship between LTTMT and a polygonal anneal and notch-bar impact strength. It was found that this treatment raised the resistance to crack initiation from 26 to 80 percent and the resistance to crack propagation 12 to 50 percent.

Coupled with the previous work on these steels, the results of this program appear to give the Soviets the capability to produce steels with ultimate strengths over 300 ksi with reductions of area of approximately 34 percent and high values of notched-bar impact toughness.

Combined Thermal-Mechanical Treatment of Soviet Low-Alloy, High-Strength Steels. By 1963 Soviet investigators had explored the processes of HTTMT and LTTMT quite thoroughly and realized that their advantages were significant and that these processes were a possible answer to the need for ever higher strength-to-weight materials of construction, particularly for applications in the aircraft and defense industries. All types of conventional deformation processes had been explored such as rolling, forging, extrusion, and drawing. A feeling for the effect of steel composition and temperature and degree of deformation had been gained. However, the TMT process had several inherent disadvantages. Among these were (1) an increase in directionality of mechanical properties (anisotropy), (2) inconsistency in response of materials to the treatment, (3) the problems of joining TMT components, and (4) the difficulty of translating laboratory techniques into production. In an attempt to solve some of these problems in the area of high- and ultrahigh-strength, low-alloy steels, Soviet investigators began studying the potentials of a combined TMT (HTTMT + LTTMT). The general reasoning behind these efforts was to gain toughness and ductility from HTTMT and the largest possible gains in strength from LTTMT.

Combined thermal-mechanical treatment (CTMT) encompasses many variations that will probably increase in number as investigators explore the possibilities more completely. Basically, CTMT consists of heating the steel to the proper austenitizing temperature, cooling it to the deformation temperature, plastically deforming it (or deforming it at the austenitizing temperature), cooling it rapidly to the deformation temperature for LTTMT, deforming it, and cooling it rapidly. The basic process is shown schematically in Figure 4. Some of the variations of the CTMT process include (1) quenching to room temperature from HTTMT, reheating to LTTMT deformation temperature, deforming and cooling rapidly, and (2) the same schedule as in (1) with a polygonal anneal following the rapid cooling.

Typical examples of the mechanical properties obtained by Soviet investigators in the 1963-1966 time period are given in Table 4. Although these data do not show spectacular gains in mechanical properties, there are indications of increased ductility and toughness at high strength levels. For example, at tempering temperatures of 200 and 250 C (390 and 480 F), elongation and ductility in all instances, show only minor decreases and in some instances show a small gain over those obtained with HTTMT. Tensile and yield values are, of course, higher with CTMT than with HTTMT or normal treatment (NT). However, in steels Number 3 and 4, yield strength values were about

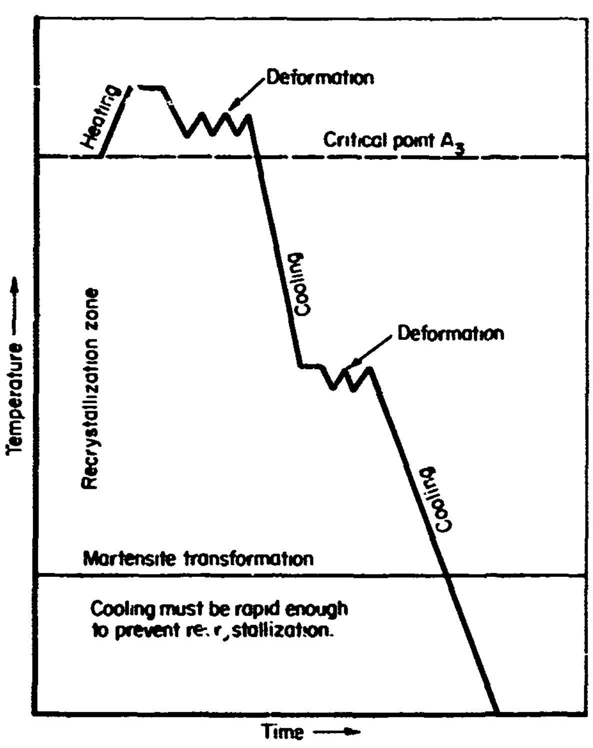

FIGURE 4. SCHEMATIC DIAGRAM OF CTMT (HTTMT + LTTMT) PROCESS FOR TREATMENT OF STEELS

TABLE 4. TYPICAL PROPERTIES OF SOVIET LOW-ALLOY, HIGH-STRENGTH STEELS SUBJECTED TO COMBINED TMT (HTTMT AND LTTMT)(70-73)

Type of Steel	t_a,(a) C	t_a,(a) F	Treatment	t_d,(b) C	t_d,(b) F	ε,(c) percent ε_1	ε,(c) percent ε_2	t_T,(d) C	t_T,(d) F	Tensile Strength, ksi Ultimate	Tensile Strength, ksi Yield	Ductility, percent Elongation	Ductility, percent Reduction in Area
Nr 1			HTTMT	900	1650	30	0			336	300	10	36
0.3C-1W-0.25V	1180	2155	CTMT	500	930	30	35	100	212	347	315	12	41
			NT	- -		0	0			273	228	10	43
			HTTMT	900	1650	30	0			326	300	12	45
			CTMT	500	930	30	35	200	390	335	292	11	42
			NT	- -		0	0			250	204	8	44
			HTTMT	900	1650	30	0			312	295	11	35
			CTMT	500	930	30	35	250	480	330	295	11	34
			NT	- -		0	0			258	207	16	45
Nr 2			HTTMT	900	1650	30	0			338	312	12	44
0.35C-1W	1180	2155	CTMT	500	930	30	35	100	212	358	333	9	33
			NT	- -		0	0			295	235	11	44
			HTTMT	900	1650	30	0			335	307	12	42
			CTMT	500	930	30	35	200	390	350	316	11	41
			NT	- -		0	0			278	235	10	46
			HTTMT	900	1650	30	0			327	313	10	32
			CTTMT	500	930	30	35	250	480	330	319	12	36
			NT	- -		0	0			267	232	10	40
Nr 3													
0.4C-1Ni-0.4Mo	1180	2155	HTTMT	900	1650	30	0			390	350	10	14
			CTMT	500	930	30	35	100	212	392	320	9	15
			NT	- -		0	0			295	227	18	32
			HTTMT	900	1650	30	0			355	306	10	38
			CTMT	500	930	30	35	200	390	365	313	14	38
			NT	- -		0	0			280	235	10	42
			HTTMT	900	1650	30	0			345	305	10	32
			CTMT	500	930	30	35	250	480	347	320	12	36
			NT	- -		0	0			265	228	10	40
Nr 4			HTTMT	900	1650	30	0			345	305	9	16
0.4C-1Ni-0.4Mo-0.25V	1180	2155	CTMT	500	930	30	35	100	212	347	320	11	15
			NT	- -		0	0			265	228	9	34
			HTTMT	900	1650	30	0			356	298	10	40
			CTMT	500	930	30	35	200	390	363	306	10	38
			NT	- -		0	0			283	243	9	44
			HTTMT	900	1650	30	0			367	326	9	30
			CTMT	500	930	30	35	250	480	374	326	8	38
			NT	- -		0	0			284	242	10	43
Nr 5			HTTMT	900	1650	30	0			392	- -	10	--
0.4C-2Cr-1Mn-1Si-2Ni-0.4Mo	- -	- - -	CTMT	500	930	30	35	100	212	392	- -	11	--
			NT	- -		0	0			- -	- -	--	--
Nr 6			HTTMT	900	1650	30	0	550	1010	IMPACT STRENGTH		2.2 kgm/cm^2	
0.37C-1.3Cr-3.9Ni	1150	2155	CTMT	550	930	0	60	550	1010	IMPACT STRENGTH		7.4 kgm/cm^2	
			HTTMT	900	1650	30	0	650	1200	IMPACT STRENGTH		3.2 kgm/cm^2	
			CTMT	550	930	0	60	650	1200	IMPACT STRENGTH		10 kgm/cm^2	

(a) t_a = Temperature of austenitizing.

(b) t_d = Temperature of deformation.

(c) ε = Degree of deformation, percent.
ε_1 = Deformation at HTTMT.
ε_2 = Deformation at LTTMT.

(d) t_T = Temperature of tempering.

the same for HTTMT and CTMT. Of particular interest was the increase in notch-bar impact strength exhibited by steel Number 6 after CTMT.

Investigations of this type published during 1965 and 1966 by the Soviets were followed by investigations which indicated that real progress was being made. Among these was a careful investigation of three steels processed by HTTMT, LTTMT and CTMT.[74] The compositions of the steels are:

	C	Si	Mn	Cr	Ni	W	Mo	V
Steel 1	0.41	1.02	0.4	1.23	1.63	--	0.20	0.07
Steel 2	0.40	1.03	1.10	0.22	1.44	--	0.19	0.08
Steel 3	0.31	0.24	0.52	1.30	3.40	0.80	--	--

All of the steels were austenitized at 900 C (1650 F) and each was separated into three batches. One batch of each steel was processed by HTTMT, the second by LTTMT, and the third by CTMT. Process details were as follows:

- HTTMT: Rolled 60-65 percent at 900 C (1650 F), quenched and tempered
- LTTMT: Cooled from 900 C (1650 F) to 550 C (1010 F), rolled 60-65 percent, and quenched and tempered
- CTMT: Rolled 50-65 percent at 900 C (1650 F) cooled quickly to 550 C (1010 F), rolled 25 percent and quenched and tempered.

The entire experiment was carried out three times with tempering temperatures of 200, 350, and 550 C (390, 660, and 1010 F), respectively, following the TMT treatment.

The results of this work showed that the specific strengthening effect (the increase of yield strength) for each percent of reduction was higher in all instances for CTMT than for HTTMT. The specific strengthening effects,

$$\frac{\text{Strength after TMT - Initial Strength}}{\text{Initial Strength}}$$

of CTMT and LTMT were related to the type of steel and tempering temperature as follows:

Tempering Temperature	200C (390 F) LTTMT	200C (390 F) CTMT	350C (660 F) LTTMT	350C (660 F) CTMT	550C(1010 F) LTTMT	550C(1010 F) CTMT
Steel 1	0.60	0.68	0.90	0.82	0.40	0.45
Steel 2	0.48	0.47	0.60	0.45	0.50	0.41
Steel 3	0.63	0.76	0.46	0.44	0.28	0.35

Elongation values were essentially the same for LTTMT and CTMT. Notched-bar impact values, however, consistently ran 3 to 4 foot-pounds Charpy V-notch higher for CTMT than for LTTMT. One of the most significant findings from this investigation from a practical standpoint was the reduction of required low-temperature deformation in the CTMT process. Deformation in LTTMT was either 50 or 65 percent relative to the steel in question, while only 25 percent of low-temperature deformation was necessary in CTMT to produce a total strength some 10 percent higher. Decreasing the amount of low-temperature deformation necessary for strengthening would decrease the mill problems appreciably.

Stainless and High-Alloy Steels

Soviet work on the TMT of this class of materials was first noted in 1958 and 1960 publications of a group headed by V. D. Sadovskiy.[75,76] Sadovskiy, who "fathered" the Soviet effort in HTTMT, applied this treatment to an austenitic 0.6C-4Cr-8Mn-4Ni-1W steel. Unlike prior Soviet work on TMT, the objective in this investigation was to increase the elevated-temperature tensile strength and rupture strength rather than the room-temperature properties. The results of this investigation showed that HTTMT increased the time to rupture about 3 to 4-fold (see Figure 5). It should be noted that the improvement in rupture strength at a stress of 135 ksi and a temperature of 900 C is not significant. For example, the 100-hour rupture strength at 900 C has been determined to be less for the TMT-treated alloy. However, gains in rupture life at 650 and 700 C are significant.

This initial work sparked a number of Soviet investigations, all of which were directed toward increasing the stress-rupture and/or creep strength of high-temperature austenitic stainless steels.[23,30,34,35,75-80] No startling advances were made, but a number of steels were investigated.

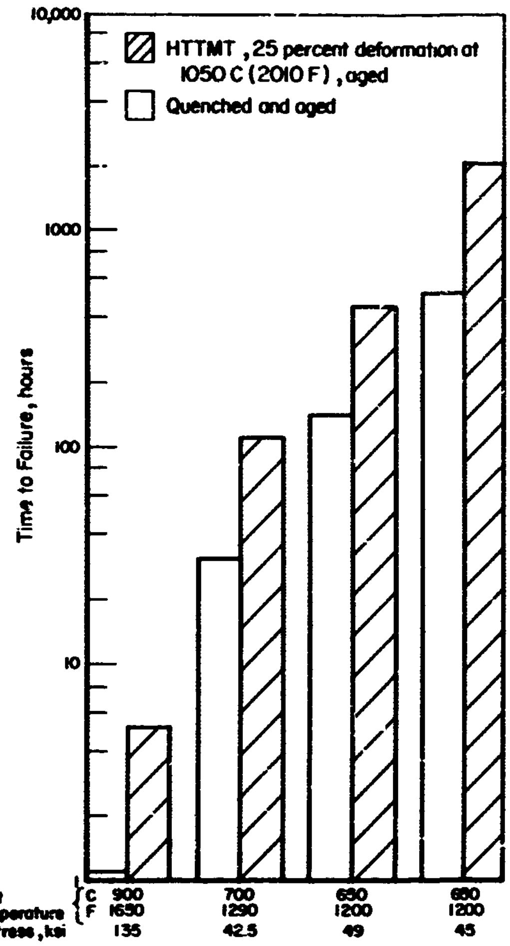

FIGURE 5. THE EFFECT OF HTTMT ON THE STRESS-RUPTURE PROPERTIES OF SOVIET STEEL 0.6C-4Cr-3Mn-4Ni-1W [75]

Among them were:

(1) 0.36C-12Cr-8Mn-8.5Ni-1.5V-1.5Mo

(2) 0.4C-12Cr-8Mn-8Ni-1V-1Mo-1W

(3) 0.14C-11Cr-1.8Ni-1.7W-0.3V

(4) 0.15C-35Ni-1W-1V

(5) 0.12C-18Cr-9Ni-0.4Ti

(6) 0.28C-19Cr-9Ni-1W-0.5V-0.4Ti.

In all instances, the time to rupture was increased from 3 to 6 times that obtained without the use of HTTMT.

One of the steels that was studied by several groups of investigators was the 0.6C-4Cr-8Mn-4Ni-1W grade. This high-temperature steel, also designated as EI 481, has long been used by the Soviets as a turbine-blade material in high-temperature engines. One of the more recent Soviet efforts in this area is a study of a newer martensitic stainless blade material-- EI 961, 0.14C-11Cr-1.8Ni-1.7W-0.3V.(79)

The increase in the high-temperature strength of stainless steels gained from HTTMT is significant. In most instances, this gain in high-temperature strength is accompanied by a gain in notched-bar impact strength at ambient temperatures. It is now known that an empirical relationship exists between impact strength and high-temperature thermal fatigue. For example, impact strength at ambient temperatures is one of the mechanical properties first considered by the British in the evaluation of a new high-temperature blade material or bucket alloy. This approach to alloy selection came as somewhat of a surprise to U. S. alloy producers when it was first encountered, since U. S. users are primarily interested in high strength properties.

Unfortunately, stainless steels do not always experience an accompanying gain in impact strength from an HTTMT treatment. An example of a combination improved high-temperature tensile strength with loss in impact strength was reported by Soviet investigators for a 0.3C-19Cr-10Ni-1Mn-1W steel.(81) Reduction of the thermal-fatigue properties by HTTMT would be anticipated in this instance. Consequently, the HTTMT of stainless steels for the improvement of high-temperature properties must be considered on an individual basis.

Soviet work on the TMT of stainless steels has been confined largely to the LTTMT of the martensitic and precipitation-hardenable grades. However improvements in fatigue strength of austenitic grades by TMT has been reported.(82,83)

Typical examples of the properties obtained by LTTMT (Table 5) show that LTTMT increased both the strength and notch-bar impact strength of both the 0.12C-12Cr-1.8Ni-1.6W-0.45Mo-0.3V and VNS-6 steels. A combination of LTTMT and tempering gives the optimum combination of strength, ductility, and toughness. A similar situation exists for the precipitation-hardenable grades.(85)

Tool Steels

The strengthening of tool steels by TMT has been well documented both in the United States and the U.S.S.R. This strengthening effect also occurs

TABLE 5. THE EFFECT OF LTTMT ON THE MECHANICAL PROPERTIES OF TWO SOVIET MARTENSITIC STAINLESS STEELS(84)

Type of Steel	Treatment(a)	Temper, C	Tensile Strength, ksi Ultimate	Tensile Strength, ksi Yield	Elongation, percent	Impact Strength, kgm/cm^2
0.12C-12Cr-1.8Ni-1.6W-0.45Mo-0.3V	Austenitize at 1020 C	No temper	256	242	15.2	6.4
	Place in furnace at 550 C, roll in 6-7 passes a total reduction of 90 percent (LTTMT)	2 hours at 500 C (930 F)	246	237	8.6	8.6
	Quenched from 1020 C No deformation	2 hours at 500 C (930 F)	206	- -	- -	5
VNS-6, 0.25C-12Cr-1.7Ni-1.7W-2Mo-0.2V	Austenitize at 1020 C	No temper	329	214	10.9	4.1
	Place in furnace at 550 C, roll in 6-7 passes a total reduction of 90 percent	2 hours at 500 C (930 F)	314	243	13.5	6.8
	Quenched from 1020 C No deformation	2 hours at 500 C (930 F)	258	- -	- -	3.3

(a) 1020 C (1870 F); 550 C (1010 F).

in practically every grade of tool steels. Consequently, the TMT of die steels and forming-tool steels does not represent any different behavior than that previously discussed for other types of steel. In the area of high-speed tool steels, however, TMT produces effects that are of specific value to these steels, namely, improvement of the cutting properties and ductility.(41,86-93)

The benefits and limitations of LTTMT are illustrated in Soviet work on the four following grades of high-speed tool steel:(94)

Steel Number	C	W	Cr	V	Mo	Co
1	0.87	9.2	4.0	2.1	0.2	- -
2	0.80	18.1	4.2	1.2	0.2	- -
3	0.80	20.2	4.0	1.8	0.16	4.7
4	0.82	8.6	4.0	1.8	0.1	10.2

The cutting properties of steels 1 and 2 were increased by LTTMT, while the cobalt-containing steels 3 and 4, were essentially unaffected. The percentage increases in distance traveled by the cutter in the direction of the surface of the machining blank before blunting of the cutting edge were 13.6 and 12.2 respectively, for steels 1 and 2. These increases were achieved with a deformation of 15 percent at a temperature of 800 C. A slightly higher increase was found at a deformation temperature of 550 C, but this gain is offset by the added difficulty of deforming the steels at this lower temperature. The ductility of the steels was increased by LTTMT 15.6, 43, 16, and 35 percent, respectively, for steels 1, 2, 3 and 4. Fracture load was also increased by 24.3, 42, 18, and 64 percent, respectively.

These findings, which are representative of the Soviet work on high-speed tool steels, represent a real gain in this area. The cutting characteristics are improved, as well as are the deflection and strength of the cutting edge. Such improvements represent an overall increase in tool life, which is the criterion for the rating of cutting tools.

One Soviet modification of TMT of tool steels is the combination of LTTMT and heat treatment in a magnetic field.(95-97) The steels in this instance were various chromium tool steels and a high-speed 18-4-1 type. The combination of LTTMT and tempering in a magnetic field* gave the following results:

Chromium Tool Steels

(1) A constant field parallel to the axis of the tool increased transverse bend strength by 65 percent

(2) A constant field normal to the axis of the tool decreased the bend strength

(3) An alternating field increased bend strength slightly.

18-4-1-Type Tool Steels

(1) A constant field parallel to the tool axis increased bend strength by 25 percent

(2) An alternating field decreased the bend strength.

Special Steels

Special steels are defined in this study as steels that are produced for a specific end use. Spring steels and ball-bearing steels are the most significant examples of steels in this category.

Spring Steels. A large amount of effort has been expended by the Soviets on the study of spring steels. All phases of the production have been considered, such as melting, fabricating, heat treatment, TMT, and, behavior in service. In the majority of instances, a single steel composition is selected, i.e., a 0.5 to 0.6C-1Cr-1Mn-0.002B grade.

Bernshteyn and his coworkers studied the TMT of spring steel from 1962 to 1967 and undoubtedly will continue their investigations.(98-102) At this point, it appears that the TMT of spring steels in the U.S.S.R. is a commercial process. All of this work was restricted to HTTMT, as the deformation of the spring steel was integrated with hot-rolling practice.

The results obtained from this program show that the strength and ductility of spring steel from the mill can be increased by HTTMT. Furthermore, these increases are not lost in subsequent tempering operations, even when multiple heat treatments are employed.

A typical schedule for the HTTMT of a 0.58C-1Cr-1Mn-0.002B spring steel is as follows. hot roll at 930-950 C (1705-1740 F), water quench, and temper to desired strength level. The properties obtained from this treatment are given in Table 6.

The improvement in properties obtained by HTTMT of these spring steels is significant, and the increase in ductility is even more significant in many instances. Water quenching of these steels without HTTMT results in cracking, but with HTTMT they can be successfully water quenched. Quenching by air blast after HTTMT instead of water quenching reduces the strength of steel tempered at 240 C (465 F) by about 14 percent; ductility values are unaffected. The strength of the steel as tempered at 650 C (1200 F) is about the same for both air and water quenching; reduction of area, however, is 23 percent higher for water quenching.

HTTMT of spring steels offers several advantages, particularly, when it is integrated into the process in a continuous hot-rolling mill. The product has higher strength and ductility, more uniform of mechanical properties, and an ability to undergo multiple treatment without loss of the HTTMT effect on mechanical properties. For example, the strip or plate that is water quenched from HTTMT temperature can be softened by tempering at 650 C (1200 F) for machining, finishing, or shaping. Then, it may be reheated into the austenite range and quenched and tempered at a low temperature, such as 240 C (465 F), to achieve a strength level equivalent to that attained by quenching an HTTMT-processed strip or plate from the HTTMT temperature and tempering at 240 C.

* Constant magnetic field of 8,000 oersteds, or an alternating field of 1,200 oersteds.

TABLE 6. THE EFFECT OF HTTMT ON THE PROPERTIES OF A SOVIET SPRING STEEL

Treatment	Tensile Strength, ksi, Ultimate	Tensile Strength, ksi, 0.2 Percent Yield	Elongation, percent	Reduction in Area, percent
HTTMT, water quench temper at 240 C (465 F)	366	334	7	18.5
Air quenched[a] and tempered at 240 C (465 F)	236	138	<1	0.8-1.5
HTTMT, water quench, temper at 650 C (1200 F)	222	198	11.5	39
Air quenched and tempered at 650 C (1200 F)	145	124	6.5	30

(a) In normal practice, the 0.38C-1Cr-1Mn-0.002B steel will crack when water quenched(after HTTMT, cracking does not occur).

Ball-Bearing Steels. The Soviet ball-bearing steel SHKI5 is a counterpart for the U. S. ball-bearing steel AISI 52100. The steel has been thoroughly researched in the U.S.S.R., primarily to remedy the need for importing steel from Sweden for ball and roller bearings. As might be expected, the Soviets attempted to improve the mechanical properties of ball-bearing grades of steel by HTTMT, and, from the results reported, they have been quite successful.(103,104) The AISI 52100 grades of steel were highly amenable to HTTMT; strength and ductility were substantially increased. For example, buckling strength* determined on flat specimens increased from 199 to 565 ksi, and deflection increased four- fold as a result of HTTMT.** There is some indication that the HTTMT of ball-bearing steels has moved from the developmental to the production stage, although this translation of technology has not been confirmed.

Rail Steels. The cracking of rail steels in service has been a traditional problem in the U.S.S.R., principally because of the low ambient temperature throughout most of the Eastern portion of the country. In recent years, the Soviets, in an attempt to further strengthen their capabilities in the manufacture of rail steels, have investigated the possibility of raising the notched-bar impact strength of these steel grades by HTTMT. The results of the Soviet work to date indicate that strength, ductility, and toughness all are increased by HTTMT.

As might be expected, most of the Soviet work on rail steels is done in commercial mills. A typical example of this activity is the HTTMT of a 0.6 to 0.7C-0.8Mn grade in a commercial two-high hot-rolling mill.(105,106) Deformation of 50 percent was achieved in one pass at a mill speed of 5.7 meters per second. The steel was water quenched as it passed through the mill.

As a result of HTTMT, these steel grades showed an increase in ultimate and yield strength of 43 and 80 percent, respectively. Elongation and reduction of area remained about the same, but notched-bar impact strength was doubled.

More recent Soviet work in this area has been directed toward the development of a steel composition that does not use critical alloying elements and that is more amenable to HTTMT. One of the better steels developed was a 0.5C-1.5Mn-0.07Ti-0.002B grade. HTTMT at 850-900 C (1560-1650 F) with only 30 percent deformation, followed by immediate water quenching and tempering at 350 C (660 F), raised the ultimate and yield strengths, respectively, about 36 and 40 percent and the impact strength by 50 percent. The reduction of area was not affected, remaining at 45 percent. Detailed studies of the microstructure did not reveal even incipient cracks from the water quench in the longitudinal, transverse, or short-transverse directions.

It is evident that the Soviets have advanced the technology of rail steels at least on a developmental basis through the use of HTTMT. There is no indication to date that HTTMT rail steels are in general use. However, in a critical application of this kind in which catastrophic failure is costly, it is quite probable that long-range, large-scale test programs would be required for certification of a new processing method.

Titanium Alloys

Titanium alloys originally were developed to meet requirements generated by the aircraft, missile, and space industries. In the United States, applications largely have remained in these areas because of cost. In a similar vein, titanium alloys were developed by the Soviet aerospace industry, as were Soviet aluminum alloys. However, applications of titanium alloys in the U.S.S.R. are not restricted to the aerospace field, but have found wide application in the chemical industry.

* Buckling strength determined in compression.

** HTTMT - 20% deformation by rolling at 930 C (1705 F), quench and temper 24 hours at 240 C (465 F).

U. S. activity in the TMT of titanium alloys has been somewhat erratic. This is due, in some part, to the fact that variations of "warm" working are often encountered in the fabrication of titanium alloys. Consequently, U. S. metallurgists have felt, with some justification, that significant increases in mechanical properties are not attainable by TMT over those presently achieved. Unfortunately, the evaulation of TMT relative to complex alloys such as the high-strength titanium alloys requires careful investigation of HTTMT, LTTMT, and CTMT relative to direct strengthening and to the preconditioning of the alloy structure for subsequent aging. Since the Soviets have systematically investigated the TMT of titanium alloys, they hold at least a temporary advantage over the United States in this area. However, in the past 2 years, considerable interest has been generated in the United States for a comprehensive evaluation of the effect of TMT on the mechanical properties of titanium alloys.

The Soviet effort on the TMT of titanium alloy has been almost entirely restricted to HTTMT. The initial investigations in 1962-1963 established the strengthening effect of HTTMT on three alloys: (a) Ti-4.6Al-2Cr-1.7Mo, (b) Ti-3Al-1.5Mn, and (c) Ti-1.7Al-1.4Mn.(45) The responses of these three alloy types were different. The strength and ductility of alloy (a) were increased. The strengths of (b) and (c) were decreased, but their ductilities were approximately doubled. This type of investigation was continued and expanded to cover two additional alloys, Ti-4Al-3Mo and Ti-4Al-3Mo-1V.(24)

On the basis of these investigations, it was found that HTTMT in the beta field primarily increases ductility and toughness. However, HTTMT in the alpha plus beta field increases strength, ductility, and toughness. A comparison of the mechanical properties obtained from optimum HTTMT and normal heat treatment are given in Table 7.

The changes in microstructure due to the HTTMT are commensurate with the changes in mechanical properties. For example, HTTMT in the alpha plus beta field prior to quenching from the solution-treatment temperature aids in the formation of large amounts of the alpha prime phase during quenching. As the amount of deformation is increased, the density of the defect structure is increased. The increased density of the defect structure in the alpha and beta phases lowers the transformation temperature.

HTTMT in the beta field, in contrast to the situation in the alpha plus beta field, increases the density of defects in the retained beta phase. However, defect density in the alpha phase remains constant. Apparently, defects generated during HTTMT are annihilated during the change in lattice structure from body-centered cubic to hexagonal close-packed. Consequently, HTTMT in the beta region increases ductility significantly with little change in strength; HTTMT in the alpha plus beta region increases strength and ductility. Various combinations of HTTMT and heat treatment yield appreciable gains in strength.

A Soviet program on titanium-alloy tubing involved the following five alloys:

(1) Ti-3Al-5.5Cr-7Mo-3Fe

(2) Ti-4Al-4V

(3) Ti-4Al-3Mo-1V

(4) Ti-3Al-6.5Mo-11Cr

TABLE 7. THE EFFECT OF HTTMT ON THE MECHANICAL PROPERTIES OF SOVIET TITANIUM ALLOYS(24)

Alloy	Treatment(a)	20 C (68 F) Ultimate Strength, ksi	Ductility, percent: Elongation	Ductility, percent: Reduction in Area	Impact Strength, kgm/cm^2	450 C (840 F) Ultimate Strength, ksi	Ductility, percent: Elongation	Ductility, percent: Reduction in Area
4.6Al-2Cr-1.7Mo	Solution treated 850 C, quenched, aged 5 hours 500 C	163	10	48	3.8	109	15	46
	HTTMT 850 C, water quenched, aged 5 hours 500 C	207	10	45	3.2	131	13	67.5
6Al-3Mo	Solution treated 880 C, quenched, aged 2 hours 590 C	165	15	43	3.6	105	18.5	63.5
	HTTMT 920 C, quenched, aged 2 hours 590 C	198	12	50	3.5	140	15	63
4Al-3Mo-1V	Solution treated 800 C, quenched, aged 12 hours 480 C	167	10	35	4.5	120	15	67
	HTTMT 850 C, quenched, aged 12 hours 480 C	182	10	48	4.5	128	17	65

(a) 480 C (895 F) 850 C (1560 F)
500 C (930 F) 880 C (1615 F)
590 C (1095 F) 920 C (1690 F).

(5) Ti-2Al-7Mo.(107-113)

However, most of the effort was concentrated on the alpha plus beta alloy, Ti-4Al-3Mo-1V, and the beta alloy, Ti-3Al-6.5Mo-11Cr. Ultimately, the latter alloy was selected as optimum. Typical properties obtained from HTTMT and LTTMT of the all-beta alloy are given in Table 8.

The next step in this program was the exploration of a combined treatment--HTTMT + LTTMT (CTMT). A schematic diagram of the CTMT process employed is shown in Figure 6. The process for fabrication and treatment of the tubing evaluated in these experiments consisted of machining the ingot, extrusion into 8-inch-diameter rod at 1100 C (2012 F), air cooling, piercing of the rod at 1100 C (2012 F), drawing of tubing at 1100 C (2012 F) (85 percent deformation), water quenching to about 200 C (390 F), rolling (50 percent reduction), and aging 5 to 25 hours at 480 C (895 F). After drawing at 1100 C (2010 F), the diameter of the tubes was 4.4 inches and thickness was 0.4 inch. After rolling, the diameter was the same 4.4 inches and wall thickness was about 0.055 inch. Additional toughness was gained by aging 15 minutes at 560 C (1040 F).

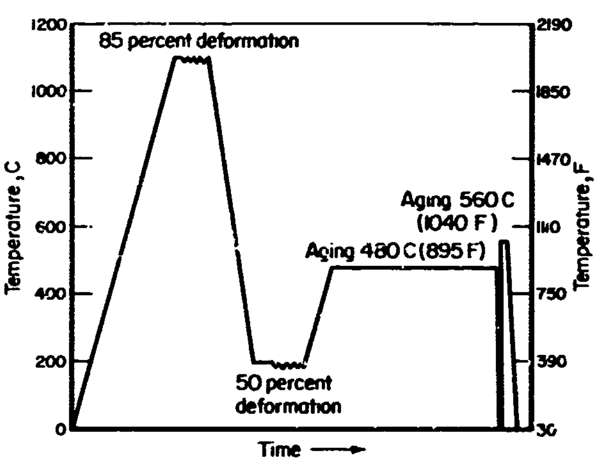

FIGURE 6. THE EFFECT OF CTMT ON THE SOVIET ALL-BETA TITANIUM ALLOY Ti-3Al-6.5Mo-11Cr

The tubes were evaluated in burst tests. Burst strength was calculated from the following expression: burst strength = $\frac{PD}{2t(100)}$, where P = the internal pressure in atmospheres, D = diameter of the tube in millimeters, and t = thickness in millimeters. Uniaxial tensile strength was obtained from stays cut from sections of tubing. The results of the test evaluation are given in Table 9.

Inspection of Table 9 shows that the CTMT treatment, with aging 5 to 10 hours at 480 C (895 F) followed by aging 1/4 hour at 560 C (1040 F), yields the best combination of strength and ductility.

One of the interesting points uncovered by this Soviet program was the mechanism of strengthening an all-beta titanium alloy by TMT plus aging. When the alloy is processed with TMT prior to aging, small needles of alpha prime phase form in the beta grains; these apparently provide a major source of strengthening, in addition to strengthening by the dislocation structure formed by TMT. The combination of HTTMT and LTTMT (CTMT) prior to aging yields optimum combinations of strength and ductility and probably will be favored by the Soviets in future efforts to utilize the TMT process.

Recent Soviet work indicates that the fatigue strength of titanium alloys is increased by TMT.(114)

Nickel-Base Alloys

The response of nickel and nickel-base alloys to TMT is almost identical to that obtained with austenitic stainless steels. The objective associated with the treatment is the same, an increase in strength at elevated temperatures.

Soviet TMT research activity on this class of materials was initiated about 1962, and has con-

TABLE 8. THE EFFECT OF TMT ON THE MECHANICAL PROPERTIES OF A SOVIET ALL-BETA TITANIUM ALLOY(109)

Treatment	Reduction, percent	Aging Time, hours	Test Temperature, C	Tensile Strength, ksi Ultimate	Tensile Strength, ksi Yield	Ductility, percent Elongation	Ductility, percent Reduction in Area	Impact Strength, kgm/cm^2
HTTMT after 30 minutes at 760 C	10	25	20 (68 F)	217	208	3.0	11.3	1.7
	10	25	400 (750 F)	180	- -	5.2	31.5	- -
	10	50	20	209	202	2.6	7.6	1.2
	10	50	400	166	- -	5.0	31.5	- -
	45	25	20	226	220	3.0	10.6	1.1
	45	25	400	175	- -	6.0	38.2	- -
	45	50	20	216	212	4.2	12.1	- -
	45	50	400	- -	- -	- -	- -	- -
LTTMT after cooling from 760 to 350 C, quenched	45	25	20	229	220	3.1	23.0	1.0
	45	25	400	177	- -	3.5	21.2	- -
	45	50	20	228	212	2.9	11.0	1.1
	45	50	400	173	- -	4.0	23.8	- -
Annealed at 750 C, water quenched	- -	25	20	179	175	7.8	31.2	- -
	- -	25	400	168	- -	6.0	28.0	- -
	- -	50	20	190	182	6.2	16.7	- -
	- -	50	400	173	- -	6.0	35.0	- -

TABLE 9. THE EFFECT OF TMT AND HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF VESSELS FABRICATED FROM A SOVIET ALL-BETA TITANIUM ALLOY[110]

Treatment[a]	Burst Pressure, atmospheres	Wall Thickness, inch	Burst Strength (BS), ksi	Tensile Strength, (TS), ksi	Elongation, percent	BS/TS
HTTMT + aging 480 C, 25 hours	351	0.0534	190	- -	- -	- -
HTTMT + aging 480 C, 25 hours + aging 560 C, 1/4 hour	390	0.0530	213	202	3.0	1.05
HTTMT + aging 480 C, 10 hours + aging 560 C, 1/4 hour	440	0.0564	200	198	6.0	1.11
HTTMT + aging 480 C, 5 hours + aging 560 C, 1/4 hour	400	0.0564	200	192	7.7	1.05
HTTMT + LTTMT + aging 480 C, 25 hours	360	0.0528	187	- -	- -	- -
HTTMT + LTTMT + aging 480 C, 25 hours + 560 C, 1/4 hour	395	0.0512	219	206	5.4	1.06
HTTMT + LTTMT + aging 480 C, 10 hours + aging 560 C, 1/4 hour	435	0.0530	237	198	8.3	1.20
HTTMT + LTTMT + aging 480 C, 5 hours + aging 560 C 1/4 hour	440	0.0556	224	195	9.1	1.13

(a) 480 C (895 F)
560 C (1040 F).

tinued up to the present.[35,67,115-121] These investigations have been approximately evenly divided between pure nickel and nickel-base superalloys.

The TMT of nickel raises its ambient and high-temperature properties and notch toughness. Of particular interest are the gains realized in rupture and creep strength. Unfortunately, these gains are lost if the temperature of operation is above 500 C. The typical response of nickel subjected to HTTMT and LTTMT and tested at 500 C (930 F) is shown in Figure 7. Stress-rupture strength is increased significantly by TMT. However, at test temperatures above 500 C (930 F), the stress-rupture strength drops rapidly. In some instances, the high-temperature properties of nickel subjected to TMT will drop below those of untreated material when tested above the 500-550 C (930-1020 F) temperature range.

The Soviets have studied the effect of TMT on the high-temperature properties of nickel-base superalloys. The effects of HTTMT on two alloys EI437B (Nimonic 80A) and EI787, a high alloy iron-base superalloy (0.08C-15Cr-35Ni-3W-3Ti-1Al-0.02 B) are shown in Figure 8. Their behavior is similar to that found for pure nickel, in which the high-temperature properties are increased for test temperatures only up to 500 to 550 C (930-1020 F). Such gains in strength are only of academic interest for nickel-base superalloys, since alloys of this type were designed for use at higher temperatures in the range of about 800-900 C (1470-1650 F) and would not be used in the 500-550 C (930-1020 F) temperature range. The usable improvement in nickel-base superalloys resulting from TMT is the gain in room-temperature notched-bar impact strength. For example, HTTMT of alloy EI437B produces a four-fold increase in room-temperature impact strength. There is a possible empirical relationship between impact strength of nickel-base superalloys at room-temperature and thermal fatigue at operating temperatures of 800-900 F (1470-1650 F). Consequently, raising the impact strength EI437B possibly would improve its thermal-fatigue resistance at operating temperatures -- 800-900 C (1470-1650 F).

Attempts to utilize HTTMT in the production of turbine blades have been reported.[122,123]

Aluminum and Aluminum-Base Alloys

Aluminum alloys appear to be one of the metallic systems in which the strengthening response of TMT is marginal; consequently, the Soviets have expended very little effort in this area.[124-126] For example, commercially pure aluminum can be strengthened approximately 25 to 30 percent by LTTMT, while Soviet alloy V-95 (equivalent to 7075 alloy) is strengthened only 5 to 10 percent. Alloys with compositions that lie between those of these two alloys will be strengthened proportionately. This rather poor showing of aluminum alloys relative to TMT is associated with decomposition kinetics. The slower the rate of decomposition of the dispersed phase, the greater the strengthening effect. Unfortunately, higher strength aluminum alloys have

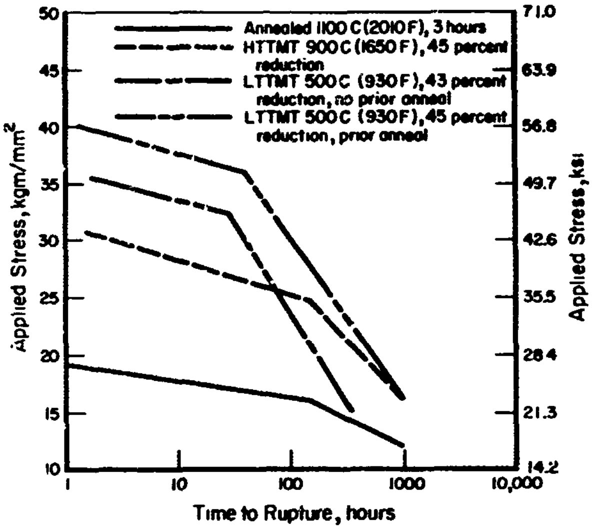

FIGURE 7. RUPTURE STRENGTH OF NICKEL AT 500 C (930 F)[121]

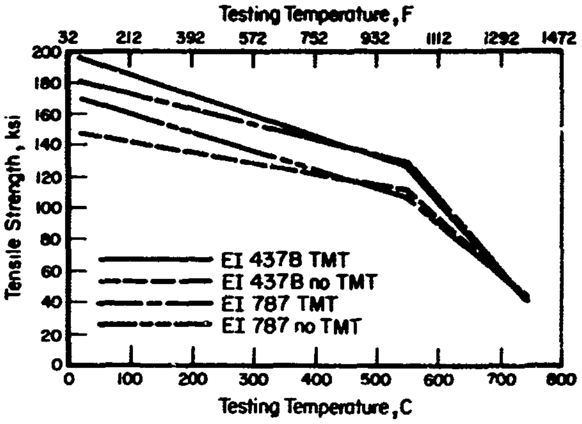

FIGURE 8. THE EFFECT OF TMT ON THE STRENGTH OF SOVIET NICKEL-BASE SUPERALLOYS[116]

a high rate of decomposition. For this reason, the HTTMT of aluminum alloys is not a practical or even a feasible method of strengthening. Consequently Soviet work in this area has been limited to LTTMT. Theoretically, there should be an LTTMT temperature that is optimum for strengthening any aluminum alloy; however, in the more complex high-strength alloys, this temperature falls only slightly above the temperature of cold working.

The effect of LTTMT on the mechanical properties of Soviet AV (commercially pure) and V95 (7075) alloys is given in Table 10. The increases in strength in the Soviet AV (commercially pure) aluminum are significant. Increases of 25 and 30 percent, respectively, in tensile and yield strength without serious loss in ductility would be of great value to fabricators of wire product. The commercial grades of pure aluminum represent the largest-tonnage production in the United States for the aluminum industry. For example, LTTMT could be applied directly to the electrical conductivity (EC) grades and other wire products such as screening.

Copper and Copper-Base Alloys

On the basis of the present understanding of TMT, some copper-containing materials should be responsive to it. However, the Soviets have neglected TMT research on copper and its alloys, except for occasional investigations of specialty items such as precision springs. Commercially pure copper (oxygen-free high-conductivity and tough pitch copper) would be strengthened by TMT, as are all of the pure metals. Nevertheless, such investigations have not been noted to date.

Soviet activity noted to date on the TMT of copper-base alloys has been limited to investigations of a Cu-62Zn alpha brass and an aluminum bronze Cu-7Al-1.5Fe.[127-129] In these studies, the authors were concerned with the effect of LTTMT on the creep and fatigue resistance and elastic stress effects in springs. In both instances, the characteristics of the springs were improved by LTTMT. For example, deformation at 200 C (390 F) of a Cu-62Zn brass spring increased the strength about five times. In a similar fashion, LTTMT of Cu-62Zn and Cu-7Al-1.5Fe spring alloys, followed by annealing, yielded increases in fatigue properties and greater uniformity of spring response than is obtained by the conventional process of cold work and anneal.

Many of the complex copper-base alloys should be amenable to TMT as a primary strengthening method and/or as a preconditioning treatment prior to precipitation or dispersion hardening. Some exploratory work in this area has been done in the United States although the results have not been published. These investigations were initiated on the basis of published Soviet work in other metal systems such as nickel and titanium.

Refractory Metals

No real Soviet effort has been noted on the TMT of refractory metals. The several publications that were reviewed proved to be concerned with various combinations of cold working and heat treatment and not TMT.

Electrical Alloys

The Soviets have initiated studies of the effects of TMT on the magnetic properties of ferromagnetic materials [130,131] and the superconductivity of niobium alloys.[132] Insufficient information is available to permit assessment of the significance of TMT in these areas.

TABLE 10. THE EFFECT OF LTTMT ON THE MECHANICAL PROPERTIES OF TWO SOVIET ALUMINUM ALLOYS(124)

Type of Alloy	Treatment[a]	Tensile Strength ksi Ultimate	Tensile Strength ksi Yield	Elongation, percent	Hardness, Rockwell B
AV (Commercially pure)	2 hours at 520 C, quench, aged 12 hours at 150 C	45.5	37	22	65
	2 hours at 520 C, quench, 20 percent deformation at 150 C, cool, aged 6 hours at 150 C	58.6	48.3	15.5	70
V95 (U.S. 7075)	2 hours at 520 C, quench, aged 12 hours at 120 C	82	60	9	82
	2 hours at 520 C, quench, 20 percent deformation at 150-200 C, cool, aged at 120 C for:				
	(a) 2 hours	85.5	67	3.5	80
	(b) 6 hours	85.5	69	7.8	83

(a) This work was done on wire 0.08 inch in diameter - deformation accomplished by wire drawing. 120 C (250 F); 150 C (300 F); 200 C (390 F); and 520 C (970 F).

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13. ABSTRACT One of the most promising methods for strengthening metallic materials that has evolved in the past 15 years is the process of thermal mechanical treatment (TMT). This process, which involves plastic deformation at elevated temperatures and retention of the "worked" structured at ambient temperature is unique--increases in strength may be attained with a gain or little loss in ductility. There are, of course, definite problems associated with the process such as the degree of temperature control required in plant operations and the negation of the TMT effect in welding processes. An analysis of the Soviet effort in TMT shows the following trends:

1. The Soviet program is broad in scope covering the TMT of steels (plain carbon, low-alloy, stainless, high alloy, and tool steels), titanium nickel, aluminum, copper and their alloys. U. S. investigators have concentrated their efforts primarily on steels (plain carbon, low-alloy, and tool steels).

2. The Soviets have explored the beneficial effects of TMT on elevated temperature properties such as creep and rupture strength of stainless and high-alloy steels and nickel and nickel-base alloys.

3. The Soviets are rapidly introducing TMT into industrial production. Several commercial rolling mills have been modified for the TMT processed rod, bar, and sheet. The TMT of tool steels for improved cutting life is apparently in the semi-production stage. Automated lines for the production of TMT treated pistons are in operation. It is anticipated that translation of their research and development programs into commercial processes will be accelerated.

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Carbon steels						
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Deformation						
Ferrous alloys						
High temperature						
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